Revista Facultad de Ingeniería
Universidad de Antioquia
ISSN: 0120-6230
revista.ingenieria@udea.edu.co
Universidad de Antioquia
Colombia

Fernández-Gómez, Wilmar Darío; Vides-Berdugo, Alba Cristina; Roncallo-Contreras, Sandra Patricia; Bautista-Rondón, Freddy; Rondón-Quintana, Hugo Alexander; Reyes-Lizcano, Fredy Alberto

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Revista Facultad de Ingeniería Universidad de Antioquia, núm. 80, septiembre, 2016, pp. 89-96
Universidad de Antioquia
Medellín, Colombia

redin Revista Facultad de Ingeniería, Universidad de Antioquia, No. 80, pp. 89-96, 2016

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UNIVERSIDAD DE ANTIOQUIA 1803

Efectos del envejecimiento ambiental y la radiación ultravioleta sobre el módulo dinámico, deformación permanente y fatiga de mezclas asfálticas

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ARTICLE INFO

Received June 04, 2015
Accepted May 04, 2016

KEYWORDS

Long term aging, performance asphalt mixtures, Superpave, field samples, INVIAS

Envejecimiento de largo plazo, desempeño de mezclas asfálticas, Superpave, muestras de campo, INVIAS

ABSTRACT: The aging process causes changes in the properties of asphalt mixtures, such as weak adhesion of mineral aggregates to the asphalt and increase of asphalt's rigidity and viscosity, which in turn directly affect the durability of asphalt pavement. This study aims to evaluate the behavior of asphalt mixtures at different aging stages through the comparison of samples treated under ultraviolet radiation and samples extracted from the field. Laboratory mixtures were prepared from one aggregate source and one asphalt cement. Four types of asphalt mixtures were analyzed: un-aged, laboratory-aged - UV and Pressure Aging Vessel, and field-aged. For laboratory accelerated aging a UV radiation chamber was designed and samples were exposed to 100, 200 and 500-hour treatment periods. Samples aged in the field were obtained from in-service pavements of 1.5 to 11 years after construction. Mechanical behavior was evaluated through dynamic modulus, rutting and trapezoidal fatigue. Results showed that when aging time increases all samples undergone significant increases in dynamic moduli up to two times of unaged mixtures. Permanent deformation exhibited better resistance in aged mixtures than the unaged ones. On the other side, aging affected negatively fatigue life due to significant changes in the slope of fatigue law. Accelerated aging by UV chamber simulated up to 1.5 years in fatigue life and 11 years in permanent deformation performance.

RESUMEN: El envejecimiento produce cambios en las propiedades de las mezclas asfálticas como debilitar la adhesión asfalto - agregado y el incremento de la rigidez y la viscosidad del asfalto. Adicionalmente, esos cambios afectan la durabilidad del pavimento asfáltico. El objetivo de este estudio es evaluar el comportamiento de las mezclas asfálticas bajo diferentes condiciones de envejecimiento comparando muestras sometidas a envejecimiento en cámara de radiación UV y otras extraídas de vías en terreno. Las mezclas de laboratorio se fabricaron con material granular de una fuente y un cemento asfaltico. Cuatro grupos de mezclas se analizaron: No envejecidas, envejecidas en laboratorio mediante UV y Vaso de envejecimiento presión y envejecidas en campo. Para el tratamiento de envejecimiento por radiación ultravioleta, se diseñó una cámara y las muestras se trataron en periodos de 100, 200 y 500 horas. Se extrajeron muestras de pavimentos en servicio de edades entre 1,5 y 11 años después de la construcción. El comportamiento mecánico se evaluó mediante ensayos de modulo dinámico, deformación permanente y fatiga trapezoidal. Lo resultados mostraron que el envejecimiento incrementa la rigidez del material hasta dos veces con respecto al material sin envejecer. La deformación permanente muestra un mejor desempeño en las muestras envejecidas que en aquella sin exposición al envejecimiento. Por otro lado, el envejecimiento afecta de manera negativa la vida de fatiga dado que se presentan cambios significativos en la pendiente de la ley de fatiga. El envejecimiento acelerado mediante la cámara de radiación ultravioleta simuló hasta un año y medio de vida a fatiga y hasta once años en la deformación permanente.

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ISSN 0120-6230
e-ISSN 2422-2844

DOI: 10.17533/udea.redin.n80a10

1. Introduction

A big challenge for pavement researchers is to carry out accelerated pavement tests for predicting field performance. These tests help to reduce the uncertainty between design models and analysis techniques that otherwise could only be verified under normal traffic and aging in real time [1]. Despite the current popularity of accelerated pavement testing, most studies have focused on mechanical materials response instead of aging effects, although it is an important distress, besides traffic loads, affecting the surface of asphalt pavements and causing a reduction of durability.

Asphalt aging is generally classified as either short or long-term [2-5]. While the former refers to the oxidation and volatilization of the asphalt binder during factory-based fabrication (including storage) and road construction (extension and compaction or laying), the latter is the result of *in situ* oxidation and hardening of the asphalt binder throughout its service life as pavement.

Aged asphalt cement (AC) generates lower adhesion between the mineral aggregates and the binder (furthering the probability of stripping) and changes in the ductile and fragile behavior of the binder and asphalt mixture (including higher levels of rigidity and viscosity). On some occasions, light AC aging turns out to be desirable on account of the associated increase in rigidity [6]. However, this "desirable" aging only applies in cases where aging does not lead to changes in the material's ductility and fragility under minimal loads. In accordance with [7], the premature failure of asphalt pavements is often attributable to the weak adhesion between the binder and the aggregate particles, due to moisture action, mechanical stress and asphalt aging.

Though aging modifies the asphalt's characteristics and usually witnesses hardening, AC oxidation has been considered to be the primary cause of hardening and embrittlement (fragility) [8,9]. Excessive hardening frequently results in embrittlement and cracking of the pavement's asphalt layer, particularly when service life entails exposure to low temperatures [8, 10, 11]. In short, the rate of hardening is affected by the asphalt's chemical composition, light exposure, aggregate properties and environmental conditions (i.e. temperature and humidity) [12-15].

The first technical study of asphalt aging was carried out in 1903 [16]. Since then, numerous researchers have studied the influence of this phenomenon on the physical, chemical, mechanical and rheological properties of AC and asphalt mixtures (AM). Laboratory and *in situ* based studies are more recent [2, 13-15, 17-19] and have been mainly focused on durability. However, on a global scale, most of the research on the aging phenomenon has been centered on AC, while there are less studies on asphalt mixtures (AM). Moreover, AC aging studies have been mainly on design procedures while AM aging studies have characterized performance along service life.

Studies on aging can be divided into four categories: a) heating; b) oxidation; c) light-based treatments; and, d) steric hardening. Heating entails subjecting the AC to high-temperature treatments; oxidation tests are performed with high temperatures and high oxidation pressures. For light-based aging, samples are directly exposed to Ultra Violet (UV) or infrared light treatments. Steric hardening refers to asphalt hardening at room temperatures as time elapses [20]. Additionally, the most common methods of evaluating AC's resistance to short (RTOFT) and long-term (PAV) aging are the Rolling Thin Film Oven Test (RTOFT) and the Pressure Aging Vessel (PAV) [21-22]. The aforementioned tests have been used as a material performance characterization in Superpave® method. Other tests, like the "Rolling Microfilm Oven Test" and the "Tilt Oven Durability Test", have also been employed to test short-term aging. For long-term aging, the "Rotating Cylinder Ageing Test" (RCAT), the "Iowa Durability Test", the "SHRP-PAV" and the "HiPAT" also appear in the pertinent scientific literature.

About AM aging, temperature treatments like Short Term Aging Oven (STOA) and Long Term Aging Oven (LTOA) according to SHRP -003A have been used to simulate aging phenomena [17]. However, evaluation of mechanical properties after laboratory treatments compared to field samples was not the same for all asphalts and asphalt-aggregate combinations [6, 23-25]. Even more, aging did not always produce detrimental effects on AM [24]. Additionally, a low-pressure oxidation treatment over AM is an alternative to high temperature aging and has proved to be more appropriate for open-graded mixtures or those with soft grades of asphalt [26].

Based on the above, and considering on one hand the scarcity of literature about accelerated aging of mixtures, and on the other hand, AM's performance in real life is affected simultaneously by temperature, pressure, humidity and radiation. So, the present study aims to recreate in laboratory environmental conditions for aging AM in order to evaluate the performance to dynamic modulus, permanent deformation and fatigue life. Furthermore, to compare these results with pavement of several years of service extracted from the field.

2. Methodology

2.1. Material Characterization

Asphalt cement 80-100, with a penetration range of 1/10 mm (ASTM D-5), was used to make the mixtures. This AC 80-100 was produced by the Colombian Petroleum company ECOPETROL S.A. in the Barrancabermeja (Colombia) factory. The performance grade (PG) of the AC 80-100 is 58-22, which is suitable for use in areas with annual average temperatures below 24°C. Table 1 presents the results of the AC physical characterization.

The mineral aggregates used to produce the asphalt mixtures were extracted from the Coello River in the department of Tolima, Colombia. Table 2 shows the physical characterization of the aggregates.

Table 1 Physical characterization of the asphalt

Test	Method	Units	PG 58-22 AC 80-100
Original Asphalt Test			
Penetration (25°C, 100 g, 5 s)	ASTM D-5	0.1 mm	83.2
Specific Gravity	INV. E-707	-	1.007
Penetration Index	NLT 181/88	-	0.3
DSR Viscosity(60°C)	ASTM D-4402	Pa-s	136
Ductility (25°C, 5cm/min)	ASTM D-113	Cm	>105
Softening Point	ASTM D-36-95	°C	50.5
Solubility in Trichlorethylene	ASTM D-2042	%	>99
Water Content	ASTM D-95	%	<0.2
Flash Point	ASTM D-92	°C	358
RTFOT Residue Test			
Mass Loss	ASTM D-2872	%	0.5
Penetration (25°C, 100 g, 5 s)	ASTM D-5	% of the original penetration	61

Table 2 Physical characterization of the mineral aggregates

Test	Method	Result
Coarse Aggregate Specific Gravity	ASTM D 854-00	2.65
Sand Equivalent	ASTM D 2419-95	58%
Fractured Faces	ASTM D 5821-01	88%
Elongation Ratio	INV. E-230	2.8%
Blue Methylene	INV. E-235	4.8%
Soundness of Aggregates (Magnesium Sulfate Attack)	ASTM C 88-99a	1.0%

2.2. Asphalt mixture design

Materials used in this study fulfill the requirements set forth by the National Institution of Highways in Colombia (INVIAS by its Spanish acronym) [27]. The aggregate's original granulometry was adjusted to meet the specifications for the production of dense hot mix asphalt with nominal aggregate size of 19 mm called MDC-19 (Table 3). Once aggregate and the asphalt binder was verified AM design was developed according to the Superpave mix design method laid out by the Standard Highway Research Program (SHRP-A-379, 1994), the optimal percentage of AC was determined to be 5.8%.

This type of mixture is the most commonly utilized in Colombia for the surface layers of pavement, which is directly exposed to the environmental factors. Laboratory samples were produced with the same characteristics than field samples. Moreover, materials used for *in situ* and laboratory-produced pavements were provided by the same asphalt mixture supplier company. Therefore, we were able to guarantee that the mixtures corresponded. Likewise, as transit loads were not taken into consideration, field samples were extracted from parking lot confinement curbs and bicycle paths.

2.3. Experimental stage

Two types of asphalt mixtures samples, slabs and cylinders, were manufactured in the laboratory. Eight slabs of 30 * 30 * 5 cm asphalt mixture were used to perform rutting, four slabs of 30 * 50 * 3 cm to fatigue testing and 30 cylinders 10 cm in diameter and 20 cm thick to develop dynamic modulus test. Slabs were compacted in a Universal Load machine with 600kPa during eight minutes and cylinders were compacted with two different air voids content, 4% and 10% in a gyratory compactor. Five trapezoidal samples for fatigue test were cut from each of the fatigue testing slabs. On the other hand, six slabs were extracted from in-service pavement, three of them for rutting evaluation and the other three for fatigue tests.

2.4. Aging treatments

Four set of samples were used for the aging experiments. The First set corresponded to unaged AM, defined as the control sample. The second set were laboratory - made samples aged in an UV chamber for periods of 100, 200 and 500 hours. Third set corresponded to AM laboratory-made of previously aged asphalt cement by PAV, following ASTM D-6521, for periods of 5, 20, and 50 hours. The fourth set of samples were those extracted from field after 1.5, 3, 5, 8 and 11 years of construction.

Table 3 Granulometry for MDC-19 asphalt mixtures

Test	Method	Result
Coarse Aggregate Specific Gravity	ASTM D 854-00	2.65
Sand Equivalent	ASTM D 2419-95	58%
Fractured Faces	ASTM D 5821-01	88%
Elongation Ratio	INV. E-230	2.8%
Blue Methylene	INV. E-235	4.8%
Soundness of Aggregates (Magnesium Sulfate Attack)	ASTM C 88-99a	1.0%

2.5. Aging chamber

For the purposes of this study, an UV chamber capable of simulating controlled environmental conditions such as UV radiation, temperature and relative humidity of 99% was constructed. This chamber has eight lamps that emit radiation in a wavelength of 340nm in the UVA range—equivalent to 0.77 W/m²/nm. The chamber employs cycles combining radiation period followed by a condensation one. The former consists in a two hour period in which UV lamps are turned on. During this period, the temperature increases up to 60°C while the UV light affects the samples. Then, it follows a two hour period when the lamps are turned off, the temperature decreases until 50°C and the sample does not receive the UV radiation.

Sample exposure times for this study were between 0 and 500 hours (250 cycles). The 340nm wavelength reflects Bogota's (Colombia) daily value of 2.2Wh/m² [28]. Hence, daily UVA radiation corresponded to 8.8 KJ/m² while annual value was 3.2 MJ/m². As the aging chamber relies on a radiation value of 1.55W/m² for each cycle (ASTM G 154-06), 500 hours of UV radiation was considered to be similar to UV conditions in Bogota (Colombia) over the course of a year.

By alternating between the two phases in the chamber, it was possible to simulate the actual exposure faced by the material in the field [29], as during the day the material is subjected to UVA exposure (lamps turned on) while the night would be considered as a "rest" period (lamps turned off), which determine the physicochemical changes undergone by the material. Moreover, to undergone that only the top side of the samples in the laboratory were UV irradiated, as occurs in field conditions, we made sure each cylinder's shafts and each slab's edges were isolated with flexible polycarbonate.

2.6. Performance evaluation

Unaged, UV and PAV aged, and field samples were evaluated with three dynamic tests: dynamic modulus, resistance to permanent deformation and trapezoidal fatigue. In the case of the dynamic modulus, the axial sinusoidal load method proposed by ASTM D 3497-03 was used. For these purposes, measurements were done at temperatures of 5, 25 and 40 °C and at frequencies of 1, 4 and 16 Hz. Master curves for these samples were adjusted at 25°C, using CAM model [30].

Rutting tests were based on the French standard NLT 173 - 84, for which four slabs from UV and four from PAV were arranged in a chamber at 60 °C one at a time. A weighted wheel was passed over the slab surface at a normalized contact pressure of 900 ± 25 kN/m² (9 ± 0.25 kgf/cm²). Fatigue resistance tests were carried out based on the Central Laboratory of Bridges and Roads (LCPC according to its French acronym) method, which is a strain-controlled test and entails the application of sinusoidal load to trapezoidal samples supported at each extreme. Field slabs of 1.5, 3 and 5 years were used to evaluate rutting while 8 and 11 year slabs were used to valuate fatigue life.

3. Results and discussion

Asphalt mixtures exhibited enhanced resistance to permanent deformation when exposing time in the UV chamber increased (Figure 1). After 100, 200 and 500 hours in the UV chamber, the mixtures displayed lower levels of permanent deformation when compared to unaged samples (10.7, 30.8 and 47.9%, respectively). Similarly, the field mixture experienced an increase in rutting resistance with higher environmental exposure. For 1.5, 3 and 5 years of exposure, permanent deformation was even smaller (63.1%, 70.6 % and 79.8%, respectively), probably due to the increased rigidity. By virtue of regression analyses, it can be stated that 750, 900 and 1250 hours of exposure in the UV chamber would be an approximately represent aging undergone by material *in situ* at 1.5, 3 and 5 years, respectively.

Data for the 20- and 50-hour PAV aging periods proved to be quite close to that observed for 8 and 11 years of field aging, respectively as shown in Figure 2.

The fatigue life of AM diminished as sample age increased (see Figure 3). This phenomenon can be due to samples reduced their resistance as stiffness increased which has been widely reported in the literature [31-34]. Moreover, fatigue tests for mixtures aged for 500 hours in the UV chamber displayed fatigue life and resistance close to that displayed by the 1.5 years *in situ*. Hence, 700 and 1075 hours of exposure in the UV chamber represented 3 and 5 years of *in situ* aging, respectively.

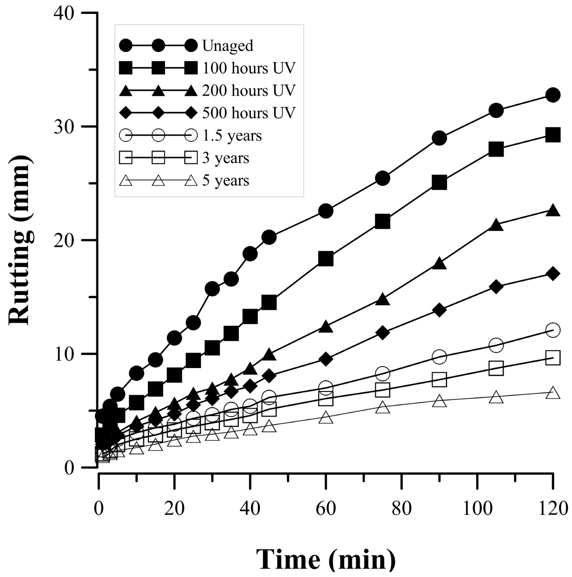

Figure 1 Evolution of the mixture's permanent deformation with and without UV aging

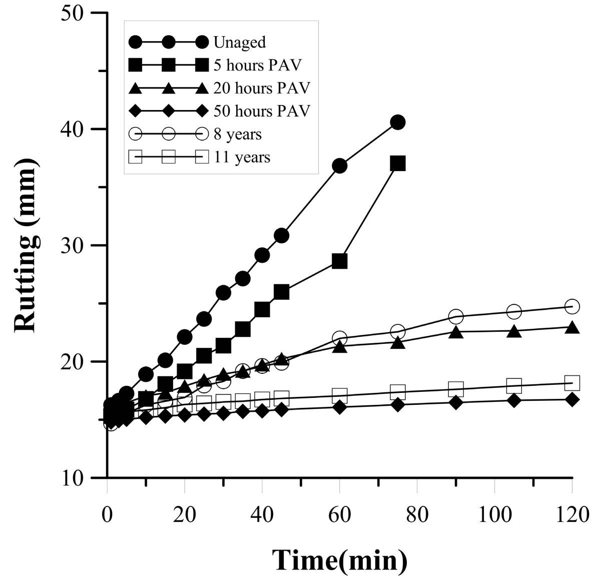

Figure 2 Evolution of the mixture's permanent deformation with and without PAV aging

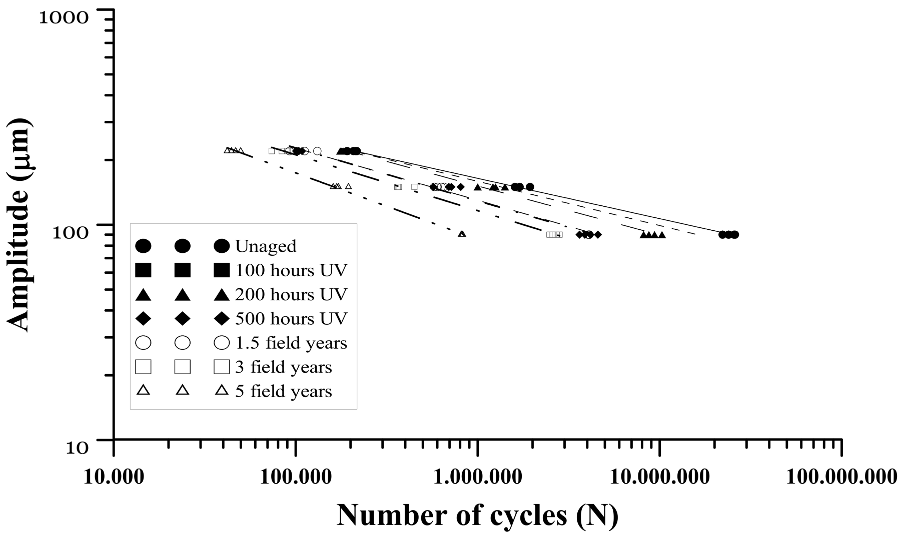

Figure 3 Evolution of the mixture's fatigue life with and without UV aging

A tendency towards growth in the fatigue law's slope was observed (Table 4). We found that aging increased fatigue law's slope 1.3, 1.4 and 1.7 for 1.5, 3 and 5 years from the control mixture, respectively. Additionally, it seems that **b** and ε_6 for 500h UV treatment is quite close to 1.5 years in the field (Table 4). Thus, environmental aging and UV radiation in laboratory can be considered as a good predictor of fatigue life.

In the case of the dynamic moduli, their growth correlates to higher exposure time (Figures 4 and 5). For all AM, higher complex modulus was observed as aging time increased, independently of air void content However, after 100 hours of UV treatment, the "open" mixtures modulus (10% voids) declined, probably due to the softening caused by the reaction among AC fractions and UV radiation. As UV radiation possesses enough energy to break up the AC molecular bonds, the aging process affects the SARA fractions. The molecular break up due to the UV radiation transforms the SARA fractions and varies their proportions, as asphaltenes and resins increase. The higher proportion of resins means that asphalts become more ductile and, as a result, the material softens [12].

Table 4 Fatigue law's slope (b) and deformation at a million load cycles (ε_6)for the MDC-19 mixtures evaluated at different stages of aging in the UV chamber and in the field

Parameter	Results						
Aging	0 h	100 h	200 h	500 h	1.5 y	3 y	5 y
Fatigue Law Slope (b)	-0.187	-0.205	-0.228	-0.242	-0.246	-0.260	-0.310
ε_6	165.44	159.94	151.02	130.92	129.30	115.94	85.05

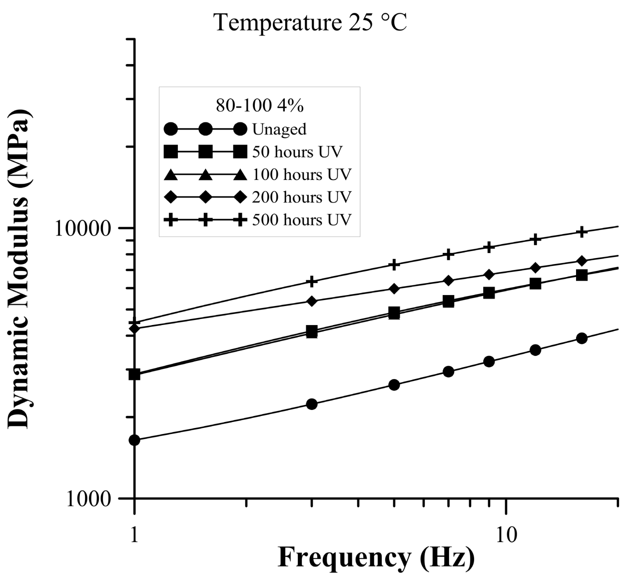

Figure 4 Evolution of rigidity in AC 80-100 with 4% air void content with and without UV aging.

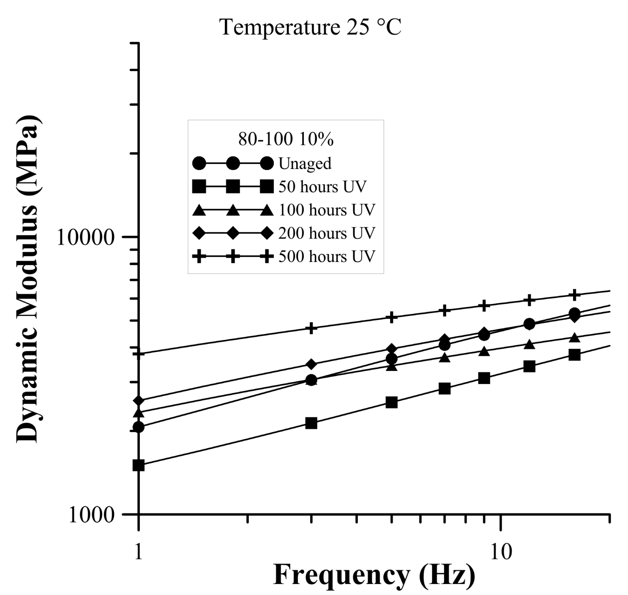

Figure 5 Evolution of rigidity in AC 80-100 with 10% air void content with and without UV aging

Whereas under 500 hours of UV aging mixtures with 4% air void content increased their stiffness up to 2.8 times of their initial modulus at 10 Hz and 25 degrees Celsius, the modulus' index of mixtures with 10% air void content increased 1.3 times more than its initial one in spite of being under the same frequency and temperature treatment. Similar results were reported by [24, 35]; however, these studies only reported twofold increases on dense asphalt mixtures.

Researchers have been developed important studies regarding performance of aged asphalts and asphalt mixtures. Regarding asphalt mixtures, few studies have considered Long Term Aging and they have only assessed from 1 to 10 days of aging temperature treatments [24, 35, 36]. In contrast, this study analyzed up to 100, 200 and 500 hours which corresponded to 4, 8 and 20 days of treatments. In addition, scarce literature has been found on accelerated aging of mixtures; thus, this research contributes to this type of testing. Moreover, this research has made important efforts in the manufacturing and sample extraction. Finally, the UV chamber was a valuable asset as it allowed to combine all variables simultaneously, imitating real conditions.

4. Conclusions

This wide-ranging experimental research on the influence of UV chamber aging on the performance of asphalt mixtures commonly used in Colombian pavements, with performance measured in terms of dynamic moduli, permanent deformation and trapezoidal fatigue provided evidence on the role played by environmental factors on the asphalt mixture's physical characteristics.

This study demonstrated that aging is not a negligible effect, as environmental variables exhibited an important effect on aging of asphalt mixtures that were not subjected to traffic loads. In that way, environmental aging and UV radiation reduced the fatigue life of asphalt mixtures. The fatigue law's slope was reduced up to 33% in the first 18 months of service life, and up to 42% during the first five years. Also, permanent deformation was reduced with service life. This reduction can reach 80% within a period of five years.

When neat asphalt was aged in the PAV, performance proved to be the same as SHRP. Thus, 20 hours of PAV aging reflected 8 years of service life approximately. However, the PAV test did not sufficiently resemble local environmental conditions to merit recognition as an indicator of aging in asphalt mixtures.

The UV chamber built for this project enabled the recreation of the effects of aging faced by asphalt mixtures in the field—especially throughout the early stages of aging—and allowed parallels to be drawn between UV chamber exposure time and field exposure time. It is necessary to mention that this is one of the first approach reported to analyze behavior of asphalt mixtures under effects of combined external agents like temperature, ultraviolet radiation and moisture in controlled conditions.

5. Acknowledgments

The authors would like to thank the Pontificia Universidad Javeriana for its support of this project (Project 4686). The authors would also like to acknowledge the valuable contributions of Concrescol S.A., the source of the materials used. Last but not least, the authors are grateful to Joseph Wager and Angela Parrado for their help in matters of English syntax.

6. References

1. L. Plesis, N. Coetzee, T. Hoover, J. Harvey and C. Monismith, "Three Decades of Development and Achievements: The Heavy Vehicle Simulator in Accelerated Pavement Testing", in *GeoShanghai*, Shanghai, China, 2006, pp. 45-54.
2. G. Airey, "State of the Art Report on Ageing Test Methods for Bituminous Pavement Materials", *International Journal Pavement Engineering*, vol. 4, no. 3, pp. 165-176, 2003.
3. S. Brown and T. Scholz, "Development of laboratory protocols for the ageing of asphalt mixtures", in *2nd Eurasphalt and Eurobitume Congress*, Barcelona, Spain, 2000, pp. 83-90.
4. C. Chiu, M. Tia, B. Ruth and G. Page, "Investigation of laboratory aging processes of asphalt binders used in Florida", *Transportation Research Record*, no. 1436, pp. 60-70, 1994.
5. A. Montepara and F. Giuliani, "Performance testing and specifications for binder and mix. Comparison between ageing simulation tests of road bitumen", in *2nd Eurasphalt and Eurobitume Congress*, Barcelona, Spain, 2000, pp. 518-523.
6. H. Khalid, "A new approach for the accelerated ageing of porous asphalt mixtures", *Proceedings Institution of Civil Engineers- Transport*, vol. 153, no. 3, pp. 171-181, 2002.
7. O. Kim, C. Bell, J. Wilson and G. Boyle, *Development of laboratory oxidative aging procedures for asphalt cements and asphalt mixtures*, 1986. [Online]. Available: http://ntl.bts.gov/lib/41000/41700/41767/Dev__of_Lab_Oxid.pdf. Accessed on: Apr. 15, 2016.
8. J. Petersen, *A Review of the Fundamentals of Asphalt Oxidation. Chemical, Physicochemical, Physical Property, and Durability Relationships*, 2009. [Online]. Available http://onlinepubs.trb.org/onlinepubs/circulars/ec140.pdf. Accessed on: Feb. 14, 2015
9. S. Jung, L. Walubita, A. Martin and C. Glover, "Mixture Versus Neat-Film Binder Oxidation and Hardening and the Impact of Binder Oxidation on Estimated Mixture Fatigue Life", in *86th Transportation Research Board Annual Meeting*, Washington, D.C., USA, 2007, pp. 18.
10. J. Wu and G. Airey, "The Influence of Aggregate Interaction and Aging Procedure on Bitumen Aging", *Journal of Testing and Evaluation*, vol. 37, no. 5, pp. 402-409, 2009.
11. Y. Ruan, R. Davison and C. Glover, "An Investigation of Asphalt Durability: Relationships Between Ductility and Rheological Properties for Unmodified Asphalts", *Petroleum Science and Technology*, vol. 21, no. 1-2, pp. 231-254, 2003.
12. W. Fernández, H. Rondón, C. Daza and F. Reyes, "The effects of environmental aging on Colombian asphalts", *Fuel*, vol. 115, pp. 321-328, 2014.
13. S. Wu, L. Pang, G. Liu and J. Zhu, "Laboratory Study on Ultraviolet Radiation Aging of Bitumen", *Journal of Materials in Civil Engineering*, vol. 22, no. 8, pp. 767-772, 2010.
14. C. Lau, K. Lunsford, C. Glover, R. Davison and J. Bullin, "Reaction Rates and Hardening Susceptibilities as Determined from Pressure Oxygen Vessel Aging of Asphalts", *Transportation Research Record*, no. 1342, pp. 50-57, 1992.
15. D. Lesueur, "The colloidal structure of bitumen: Consequences on the rheology and on the mechanisms of bitumen modification", *Advances in Colloid and Interface Science*, vol. 145, no. 1-2, pp. 42-82, 2009.
16. A. Dow, "Asphalt Experiments at Washington", *Eng. News Rec.*, vol. 47, pp. 18-25, 1903.
17. A. Bell, "Summary Report on the aging of asphalt-aggregate systems", Strategic Highway Research Program, Corvallis, USA, Rep. SHRP-A-305 (SR-OSU-A-003A-89-2), Nov. 1989.
18. C. Bell, M. Fellin and A. Wieder, "Field Validation of Laboratory Aging Procedures for Asphalt Aggregate Mixtures", *Journal of the Association of Asphalt Paving Technologists*, vol. 63, pp. 45-80, 1994.
19. J. Welborn, "Physical Properties as Related to Asphalt Durability: State of the Art", *Transportation Research Record*, vol. 999, pp. 31-36, 1984.
20. J. Masson, P. Collins and G. Polomark, "Steric hardening and the ordering of asphaltenes in bitumen", *Energy and Fuels*, vol. 19, no. 1, pp. 120-122, 2005.
21. D. Anderson, D. Christensen and H. Bahia, "Physical properties of asphalt cement and the development of performance-related specifications", *Journal of the Association of Asphalt Paving Technologists*, vol. 60, pp. 437-475, 1991.
22. H. Bahia and D. Anderson, "The pressure aging vessel (PAV): a test to simulate rheological changes due to field aging", in *Physical Properties of Asphalt Cement Binders*, J. Hardin (ed). Philadelphia, USA: American Society for Testing Materials (ASTM), 1995, pp. 67-88.
23. J. Harvey, T. Lee, J. Sousa, J. Pak and C. Monismith, "Evaluation of fatigue and permanent deformation properties of several asphalt-aggregate field mixes using strategic highway research program A-003A equipment", *Transportation Research Record*, no. 1454, pp. 123-133, 1994.
24. J. Harvey and B. Tsai, "Long-Term Oven-Aging Effects on Fatigue and Initial Stiffness of Asphalt Concrete",

Transp. Res. Rec., no. 1590, pp. 89-98, 1997.

25. G. Kemp and N. Predoehl, "A comparison of field and laboratory environments on asphalt durability", in *Association of Asphalt Paving Technologists*, vol. 50, pp. 492-537, 1981.
26. C. Bell, Y. AbWahab, M. Cristi and D. Sosnovske, "Selection of laboratory aging procedures for asphalt-aggregate mixtures", Strategic Highway Research Program, Washington, USA, Rep. SHRP-A-383, Mar. 1994.
27. Instituto Nacional de Vías (INVIAS), *Normas de ensayos de materiales para carreteras*. Bogotá, Colombia: INVIAS, 2013.
28. Ministerio de Minas y Energía (MinMinas) / Instituto de Hidrología, Meteorología y Estudios Ambientales de Colombia (IDEAM), *Atlas de Radiación solar de Colombia*, 2005. [Online]. Available: http://www.upme.gov.co/Atlas_Radiacion.htm. Accessed on: January 25, 2016.
29. M. McGreer, *Weathering Testing Guidebook*. Chicago, USA: Atlas Electric Devices Company, 2003.
30. M. Zeng, H. Bahia, H. Zhai, M. Anderson and P. Turner, "Rheological modeling of modified asphalt binders and mixtures", *Journal of the Association of Asphalt Paving Technologists*, vol. 70, pp. 403-441, 2001.
31. P. Baburamani, "Asphalt fatigue life prediction models: a literature review", ARRB Group Limited, Melbourne, Australia, Research Rep. ARR 334, 1999.
32. H. Benedetto, C. Roche, H. Baaj, A. Pronk and R. Lundström, "Fatigue of bituminous mixtures", *Materials and Structures*, vol. 37, no. 3, pp. 202-216, 2004.
33. J. Epps and C. Monismith, "Fatigue of asphalt concrete mixtures-summary of existing information", in *Fatigue of Compacted Bitumonius Aggregate Mixtures*. B. Gallaway. New York, USA: American Society for Testing Materials (ASTM), 1972, pp. 19-45.
34. L. Francken, *Bituminous Binders and Mixes*. London, UK: Rilem, 2004.
35. C. Bell, Y. AbWahab and M. Cristi, "Investigation of Laboratory Aging Procedures for Asphalt-Aggregate Mixtures", *Transportation Research Record*, no. 1323, pp. 32-46, 1991.
36. L. Walubita *et al*., *HMA Shear Resistance, Permanent Deformation, and Rutting Tests for Texas Mixes: Year-1 Report*, 2014. [Online]. Available: http://ntl.bts.gov/lib/51000/51800/51806/0-6744-1.pdf. Accessed on: Apr. 15, 2016.